Energy Price and Groundwater Extraction for Agriculture: Exploring the Energy-Water-Food Nexus at the Global and Basin Levels

Tingju Zhu[1], Claudia Ringler[1], Ximing Cai[2]

Abstract

As oil prices have climbed to unprecedented heights the concern over sustainable energy use has intensified globally. Increased energy prices could have direct adverse impacts on some of the world's largest bread bowls like the Indo-Gangetic Plains, Northern China, and the western United States, due to their large and growing reliance on energy-intensive groundwater extraction for irrigation. This paper studies the effects of energy prices on global groundwater extraction with a global water and food model, IMPACT-WATER, through analyses of a set of alternative scenarios of energy price and water management policies. In addition, increasing energy prices are also simulated at the basin level for the example of the Dong Nai basin in southern Vietnam to examine the impacts on crop production and farmer incomes.

1. Introduction: Groundwater—A Curse or Blessing?

As a result of technological advances, groundwater use has spread rapidly in recent decades, increasing reliability of irrigation supplies, encouraging crop diversification and expanding the cropping season. Global, annual groundwater withdrawals have been estimated at 670–800 km^3. India, China, the United States, and Pakistan alone extract groundwater in the order of 325 km^3 every year (Shah et al. 2000; Shiklomanov 1998).

Groundwater usage has brought many benefits to people. Its development has supported increased food production and has led to significant increases in farm incomes, including for the poor. Groundwater pumping can be tailored to individual crops, conserving irrigation water. Moreover, as pumping is generally located close to where water is being used, distribution losses in the form of evaporation and seepage are minimized. Pumping directly translates into (transparent) irrigation service costs, which increases accountability. Furthermore, as groundwater pumping entails relatively higher variable costs of delivery, as well as full water control, water use efficiency in groundwater systems is generally higher. Finally, groundwater systems can be developed by small-scale farmers, often resulting in cost savings compared to large-scale surface water systems. If the water table is close to the surface, then cheap, manually operated pumps can be used (treadle pumps). Even in cases where groundwater development is costly the poor can benefit from buying water in informal groundwater markets (Palanisami 1994; Saleth 1998). Groundwater pumping has also brought immense benefits for safe drinking water supplies, particularly in rural areas. More than 1.5 billion people in the world rely on groundwater for their primary source of drinking water (Clark et al. 1996).

However, rapid expansion of groundwater use has also led to groundwater mining in parts of the world. The biggest problems resulting from groundwater use are overdrafting and deterioration of water quality. Moreover, excessive groundwater use reduces water availability in streams and lakes, can lead to land subsidence, and saline intrusion in coastal aquifers (Rosegrant 1997).

Groundwater pumping in excess of recharge has caused significant groundwater depletion in many regions including northern China, northern India, the western United States, and countries in the West Asia and North Africa region. Groundwater overdraft can lead to significant problems in both water quality and water availability; thus, excessive groundwater use is a critical policy issue in balancing water uses for food production and the environment (Rosegrant, Cai and Cline 2002). Postel (1999) draws on several sources to estimate total annual global groundwater overdraft at 163 km^3.

Most non-renewable groundwater resources of the world are distributed in Africa, especially the northern part of the continent, where the renewable water resources are most scarce and the interest in such aquifer systems is greatest. Mining of non-renewable groundwater resources accounts for a small portion (~ 4%, as estimated by Margat et al., 2006) of the total groundwater exploitation globally. Saudi Arabia and Libya account for 77 percent of the estimated global world extraction of non-renewable groundwater. In both these cases non-renewable groundwater represents an important or predominant source of water-supply (84% in Saudi Arabia and 67% in Libya), and is used for urban water-supply as well as irrigated agriculture.

Excessive groundwater pumping can lead to the drying up of more shallow wells, requiring deeper tubewells, and increased pumping cost. As the depth to water increases, the water must be lifted higher to reach the land surface. If pumps are used to lift the water (as opposed to artesian wells), more energy is required to drive the pump. Using wells can thus become prohibitively expensive.

India

In India, about 60 percent of the irrigated food grain production now depends on groundwater irrigation and about half of total area irrigated depends on groundwater wells. The number of shallow tubewells roughly doubled every 3.7 years between 1951 and 1991. In general, groundwater irrigators in poorer states tend to rely more on diesel (see Figure 1). Research in India showed that groundwater irrigated crops generally result in higher yields due to better water control, as compared to surface-irrigated crops (Shah et al. 2000; Singh and Singh 2002). However, overdraft has taken on alarming proportions in several states, and has led to increased competition among irrigators, but also between irrigation and domestic water users. Subsidized energy for groundwater pumping is a major contributor to groundwater overdraft in the country.

China

With limited supplies and rapidly growing demands, northern China is particularly water-stressed (Wang, et al. 2005). According to China's Ministry of Water Resources (2001), between 1958 and 1998 groundwater levels in the Hai River basin fell by up to 50 meters in some shallow aquifers and by more than 95 meters in some deep aquifers. According to Huang et al. (2006) farm households in China pay for the cost of energy (electricity or diesel) to pump the water, based on hours of operation, kilowatt hours, or electricity used. In informal water marketing situations, service fees are often added.

USA

In the United States, groundwater provides about 50 billion gallons per day (69 km^3 per year) for agricultural needs. Groundwater depletion has been a concern in the Southwest and High Plains for many years, but increased demands on water resources have led to overdraft in other areas as well. In the Atlantic Coastal Plain aquifer, for example, pumping water for domestic supply has lowered the water table, reduced or eliminated the base flow of streams, and has caused saline ground water to move inland. In west-central Florida, groundwater development has led to saltwater intrusion and land subsidence and concerns about surface water depletion from lakes in the area. In the Houston, Texas, area, extensive groundwater pumping to support economic and population growth has caused water level declines of approximately 400 feet (122 meters), resulting in extensive land-surface subsidence. The High Plains aquifer (which includes the Ogallala aquifer) underlies parts of eight States and has been intensively developed for irrigation. Since predevelopment, water levels have declined more than 100 feet in some areas and the saturated thickness has been reduced by more than half in others. In the desert southwest of the United States, increased groundwater pumping to support population growth in south-central Arizona has led to drops in the water table of 300-500 feet and resulted in the loss of streamside vegetation. Similarly, in the Chicago-Milwaukee area, long-term pumping has lowered groundwater levels by around 900 feet (274 meter).

2. Evidence on the Energy-Groundwater Nexus

At this point there is little evidence that rising energy costs adversely impact food security in the major breadbowls relying on groundwater. Groundwater extraction in India is fueled by electricity and diesel, both of which are provided at subsidized rates to farmers by state governments. Changes in energy prices are absorbed by the government, especially in the case of electricity tariffs.

In China, the electricity price did not increase much compared to oil because thermal plants mostly burn coals, and the share of energy production from hydropower is increasing. Most pump sets are run with electricity.

In the United States, environmental concerns together with farm support and other government policies are more important drivers of groundwater use than energy cost. Anecdotal evidence, however, indicates some changes in cropping pattern and energy sources for groundwater pumping in areas of the United States. In Arkansas, growers are said to have reduced rice areas, generally in favor of increased soybean, because of a combination of increased fertilizer and energy prices (Earl D. Vories, personal communication, January 2007). Moreover, in the Ogallala aquifer higher pumping costs have led to the shutdown of some fossil fuel powered pumps, as the price of diesel was three times the cost of electricity (Robert Evans, personal communication, January 2007).

While there is little evidence to date on reductions in groundwater pumping as a result of higher energy cost, sharp further increases in energy prices are plausible. The following sections examine the potential impact of rapid energy price increases on food supply and demand and farm incomes based on a global water-and-food projections model and for a basin setting, respectively.

3. Simulations for the Energy-Water & Food Nexus at the Global Scale

Introduction of the Global Water and Food Model: IMPACT-WATER

The IMPACT-WATER model consists of a global food supply, demand and trade model and a global river-basin-based water simulation model (Rosegrant et al. 2002), as illustrated in Figure 2. The model was recently updated to include 115 global economic regions, most of which overlap with countries, 126 global river basins, of which some are aggregated river basins, and 281 global food production units (FPU) defined by intersections of economic regions and river basins, as shown in Figure 3. The 126 major river basins in the world were defined in a way that serve the need of achieving accuracy with regard to the basins most important to irrigated agriculture.

The water simulation model operates at FPU level. For each FPU, long-term water demands are projected for domestic, industrial, irrigation, and livestock sectors based on drivers including population and income growth, growth of irrigated areas and change of cropping patterns. Industrial demands are projected for each of three major industrial classes separately. Livestock water demands are projected for each of the six livestock types in the model. On the supply side, long-term historical monthly time series of precipitation, potential evapotranspiration (ET) and runoff (surface runoff plus groundwater recharge) for each FPU are used to represent future climate scenario. Other sources of water like desalinization are also considered.

The water simulation model then optimizes water supply according to demand based on the projected future infrastructure capacity and environmental policy, including improvement of basin water use efficiencies, surface water storage and surface and groundwater withdrawal capacities, and environmental constraints like instream flow requirements. Total available water is allocated to sectors and crops on the basis of pre-defined allocation rules.

The IMPACT-WATER food model covers more than 30 agricultural commodities including all cereals, soybeans, roots and tubers, vegetables and fruits, fiber crops, meats, milk, eggs, oils, and meals. It is defined as a set of regional sub-models. Within each country or regional sub-model, supply, demand, and prices for agricultural commodities are determined. These country and regional agricultural sub-models are linked through trade. Supply and demand functions incorporate supply and demand elasticities to approximate the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets. Essentially, this partial equilibrium agricultural sector model simulates the behavior of a competitive world agricultural market for crops and livestock.

Linking Energy Price and Groundwater Use in IMPACT-WATER

Groundwater aquifers are much localized resources and there is no straightforward way to simulate groundwater dynamics with a single global modeling framework without explicitly including the details associated with local climate, topology, and hydrogeologic properties of aquifers. In our policy modeling framework, therefore, the responses of groundwater depth to groundwater pumping are not explicitly represented. Instead, to simplify the analysis and focus on the impacts of energy prices, we assume the groundwater depth would be relatively stable over a long period of time in the future, and thus the total costs of extraction are only affected by the volume of groundwater extracted and the unit price of energy.

The energy required for groundwater pumping equals

$$E = \phi \cdot W \cdot h \qquad (1)$$

where E is the total energy (in million watt hours, Mwh) used in pumping out W million cubic meters of ground water from an aquifer; h represents average groundwater depth from land surface during the period of pumping, and ϕ is a coefficient defined by

$$\phi = \gamma \cdot \rho \cdot g / 1000 \qquad (2)$$

in which γ is pumping efficiency (usually 0.4-0.7, dimensionless), ρ is density of water (1000 kg/m^3) and g is the acceleration of gravity (9.8 m/s^2).

With the above assumption that groundwater depth would be relatively stable, from Equations (1) and (2), energy consumption of groundwater pumping would be proportional to the volume of water extracted from aquifers. Though tending to oversimplifying, the assumption allows us to link energy price to water use in a straightforward way.

Within a year, if the volume of groundwater being used in FPU u and month m is $GW_{u,m}$, and surface water use is $SW_{u,m}$, then the percentage of groundwater use in this year is

$$\alpha_u = \frac{\sum_m GW_{u,m}}{\sum_m SW_{u,m} + \sum_m GW_{u,m}} \qquad (3)$$

Assuming the energy price increases by a percentage of ΔPE, from Equation (1), the cost of groundwater pumping will be increased by the same percentage. Without considering other cost changes of supplying groundwater to end users, we assume the increase of groundwater supply cost will also increase by ΔPE, which can be justified in many places where pumping cost is the primary cost of groundwater. Since the cost increase of surface water supply due to higher energy price is relatively difficult to quantify, and could be small compared with the changes of cost of groundwater, we further assume that surface water supply cost would remain unchanged. So, if the original water price for water use sector s is $P_{u,s}$, the water price with increased energy price equals

$$P_{u,s}' = \left(1 + \alpha_u \cdot \Delta PE\right) \cdot P_{u,s} \qquad (4)$$

where α_u is the ratio of the quantity of groundwater use to total water use in the FPU.

In the water simulation model, originally projected water demand for each sector in a FPU is adjusted by a demand function of relative water price, as below:

$$D'_{u,s}\left(RP_{u,s}\right) = D_{u,s} \cdot RP_{u,s}^{\ \eta} \qquad (5)$$

where $D'_{u,s}$ is water demand of sector s in FPU u, $D_{u,s}$ is originally projected water demand, $RP_{u,s}$ represents relative water price, and η denotes price elasticity of water demand for sector s in FPU u. The relative water price also changes over time, reflecting the change of a users' financial capability of obtaining and using water, and the changes of a region's situation of water supply and demand. Price elasticities of irrigation water demand for selected countries are shown in Figure 4.

Higher energy prices also raise the costs of diverting surface water, and the costs of water treatment to meet the standards for drinking and industrial uses. Costs of desalinization will likely increase as well. However, to focus on the impacts of groundwater pumping, these impacts are not included.

With this simple linkage between water price and energy price, we are able to preliminarily examine the impacts of energy price increase on water supply and food security.

Results

In this paper, we analyzed three hypothetical scenarios of energy price change, without explicitly separating the types of energy for pumping uses, such as electricity or diesel: baseline (no change of energy price), doubled energy price, and tripled energy price for groundwater pumping.

Figure 5 shows the global total consumptive irrigation water use under the three energy price scenarios. On average, irrigation water depletion decreases by 7.5 percent from the baseline under the doubled price scenario, and by 9.1 percent under the tripled energy price scenario. Despite this sharp increase in energy price, consumption declines are large but not alarming, because the price elasticity of water demand is relatively low, particularly for the irrigation sector (Figure 4). In addition, surface water irrigation accounts for the larger share of irrigated food production.

Global cereal production declines only slightly under the alternative energy price scenarios. The change of average production from the baseline to the doubled price is -0.80 percent and the change from baseline to the tripled price is -0.94 percent. For both doubled price and tripled price, reductions in cereals production are not significant, much lower than the magnitude of inter-annual production variability caused by climate and hydrology variability, which affect crop yield reduction due to water stress.

The world prices over the future decades for rice and maize are shown in Figures 6 and 7. As a result of higher energy prices, world prices for agricultural commodities increase, by 4 and 4.8 percent, on average, for maize under the double and triple scenarios; by 5.2 and 6.2 percent for wheat, and by 4.2 and 5.0 percent for rice, respectively. Declines in water consumption in China lead to slight increases in net cereal imports, while for India net cereal exports decline. Impacts on the United States are smaller, and food price increases actually lead to an increase in its net export position for cereals.

4. Energy-Water & Food Nexus at the Basin Level

An integrated hydrologic-economic river basin model is used to examine the impact of increased groundwater pumping cost on food production and farmer incomes for the case study of the Dong Nai River Basin in southern Vietnam.

The basin model describes the water supply situation along the river system and the water demands by the various water-using sectors. Water benefit functions are developed for productive water uses, and minimum instream flows are included as constraints. Water supply and demand are then balanced based on the economic objective of maximizing net benefits from water use. This structure allows for intersectoral and multiprovince analyses of water allocation and use with the objective of determining tradeoffs and complementarities in water usage and strategies for the efficient allocation of water resources (for more details see Ringler et al. 2006).

Groundwater use in the Dong Nai basin

While the share of agriculture in total GDP in the Dong Nai basin has been declining over time, the agricultural sector in the basin is highly diversified and dynamic, with products ranging from basic staples like rice and maize to raw materials for the local industry, including rubber and sugarcane, to high-value crops like coffee, flowers, fruit, pepper, tea, and vegetables. Rapid groundwater expansion in the basin and elsewhere in Vietnam has catapulted the country to become the largest pepper exporter globally and the second largest pepper producer (after India); and the second largest coffee exporter for the *robusta* coffee variety.

Based on a household survey covering 700 households implemented for 2000-2001 in the 11 provinces of the Dong Nai River Basin, 397 irrigated crop observations (out of a total of approximately 1,600 observations) relied on groundwater irrigation, including 23 for coffee; 52 for cereals; 106 for fruit trees, and 216 for vegetable crops. Thirty-five percent of irrigators used diesel and the reminder electricity. Average energy cost per hectare per crop using groundwater was US$70 for fuel and US$43 for electricity. Even though these costs are fairly high, they constituted only 6.6 percent and 3.4 percent of total crop costs, respectively, for fuel and electricity use (based on a simple average across crop observations). The share of labor (40 percent) and fertilizer and pesticides combined (40 percent) in total cost were significantly higher.

Alternative Energy Cost Scenarios, Dong Nai basin

As groundwater data in the basin are scarce, the model only includes the exploitation capacity of shallow groundwater as well as available withdrawal estimates by sector treating each aquifer as a provincial-level tank. Groundwater pumping costs from survey estimates were converted into volumetric estimates, with average rates for groundwater irrigation of US$0.05/$m^3$. Rates for industrial and domestic uses of US$0.07/$m^3$ are based on interviews of water supply companies. Irrigation service fees for surface water irrigation are much lower, ranging from US$ 0.00034/m^3 to US$ 0.40139/m^3 depending on the crop and season. Groundwater pumping accounts for 4 percent of total irrigation withdrawals in the basin. Moreover, groundwater pumping for irrigation accounts for 36 percent of total pumping in the basin.

Two alternative pumping cost scenarios are modeled: one doubling base pumping cost, and the second one tripling energy cost, for all water-using sectors drawing on groundwater. The results are presented in the following.

With a doubling of energy or pumping cost, total groundwater withdrawals decline by 42 percent or 307 million cubic meters. With a tripling of energy costs, the decline is 56 percent or 406 million cubic meters (Figure 8). The drop in pumping for irrigation water is much larger, at 59 percent and 76 percent, respectively. Beneficial crop evapo transpiration declines from 2,110 million cubic meters under the base optimization to 2,039 million cubic meters under the tripled water use scenario. This decline is much smaller than the drop in groundwater pumping would suggest. Moreover, while total water depletion slightly declines, total withdrawals increase, as surface withdrawals compensate in part for declines in groundwater use and seepage and evaporation losses of this source are higher. Whereas pepper and fruit tree crops maintain production levels due to their relatively higher profitability, area harvested and production for coffee, which features a lower profit per unit of water, declines (Figure 9).

Thus, overall impacts on the water balance and production levels are minor. Impacts on agricultural profits are significant but not excessive (Figure 10). Agricultural incomes drop from US$404 million under the basin optimization to US$392 million under the tripled energy price scenario, a decline of 2 percent. Overall basin profit declines by US$66 million or 4 percent, as a result of higher pumping costs for industrial and domestic users.

5. Conclusions

At this point there is little evidence that rising energy costs adversely impact food security in the major breadbowls relying on groundwater. Groundwater extraction in India is largely fueled by electricity and diesel, both of which are provided at subsidized rates to farmers by the state governments. Any changes in energy prices are absorbed by the government, especially in the case of electricity tariffs. In China, the electricity price did not increase much compared to oil because thermal plants mostly burn coals, and the share of energy production from hydropower is increasing. Most pump sets in both countries rely on electricity and not on diesel to fuel pumps. In the United States, other policies are more important determinants for groundwater pumping outcomes, including environmental policies and farm support policies.

Based on a global water-and-food projections model, we show that increased energy prices for groundwater result in little reduction in global cereal production. While total irrigation consumption declines by 7-9 percent (and groundwater even more), resulting higher international food prices stimulate increased food production in rainfed areas as well as irrigated production in surface systems. Final outcomes for world food prices are relatively minor compared to the sharp increases in energy prices simulated.

The basin-level model showed similar results, using a different modeling framework. Here, the main reason for the small decline in food production is centered at the small share of groundwater pumping cost in total agricultural production costs (6.6 percent and 3.4 percent of total crop costs, respectively, for fuel and electricity use, based on a simple average across crop observations). However, impacts on net farm incomes would have been more severe if a larger share of crops would have relied on groundwater pumping.

Thus, while higher energy costs for groundwater pumping will certainly hurt small-scale farmers (and domestic users) relying on this water source, it is unlikely that sharp increases in the energy price lead to sharp declines in food production, or rapid increases in world food prices, and thus are also unlikely to help stop or reverse the ongoing degradation of groundwater ecosystems.

References

Alley, W. M., R. W., Healy, J. W., LaBaugh and T. E. Reilly. 2002. Flow and storage in groundwater systems. *Science*, 296: 1985-1990.

Clarke, R., A., Lawrence, and S.S.D., Foster. 1996. Groundwater - a threatened resource, UNEP Environment Library 15.

Coon, W. F. and R. A., Sheets. 2006. Estimate of ground water in storage in the Great Lakes Basin, United States, 2006, National Water Availability and Use Program Scientific Investigations Report 2006-5180, U.S. Geological Survey, Reston, Virginia.

Crosbie, R. S., P., Binning, and J. D., Kalma. 2005. A time series approach to inferring groundwater recharge using the water table fluctuation method, *Water Resources Research*, 41, W01008, doi: 10.1029/2004WR003077.

Huang, Q., S. Rozelle, R. Howitt, J. Wang, and J. Huang. 2006. Irrigation Water Pricing Policy in China. Mimeo.

Margat, J., S., Foster and A., Droubi. 2006. Concept and importance of non-renewable resources, In “Non-renewable groundwater resources: a guide book on socially-sustainable management for water policy makers” edited by S. Foster and D. P., Loucks, UNESCO, Paris, France.

Palanisami, K. 1994. Evolution of agricultural and urban water markets in Tamil Nadu, India. Arlington, Virginia: Irrigation Support Project for Asia and the Near East (ISPAN), United States Agency for International Development.

Ringler, C., N.V. Huy, and S. Msangi. 2006. Water Allocation Policy Modeling for the Dong Nai River Basin: An Integrated Perspective. *Journal of the American Water Resources Association* 42(6): 1465-1482.

Rosegrant, M.W. 1997. Water resources in the twenty-first century: Challenges and implications for action. Discussion Paper No. 20. Washington, D.C.: IFPRI.

Saleth, R.M. 1998. Water Markets in India: Economic and Institutional Aspects, in K.W. Easter, M.W. Rosegrant and A. Dinar (eds.), Market for Water: Potential and Performance, Kluwer Academic Publishers.

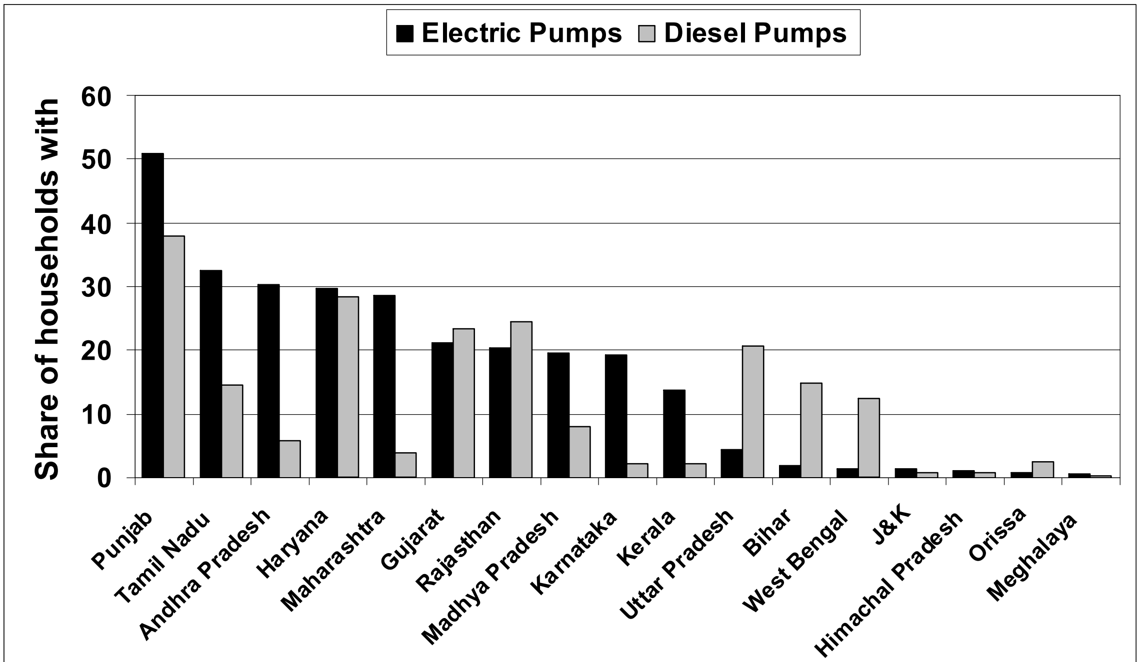
Shah, T., D., Molden, R. Sakthivadivel and D. Seckler. 2000. The global groundwater situation: overview of opportunities and challenges, International Water Management Institute, Colombo, Sri Lanka.

Singh, D. K., and A. K. Singh. 2002. Groundwater Situation in India: Problems and Perspectives. *International Journal of Water Resources Development* 18(4): 563–80.

Wang, J., S. Rozelle, A. Blanke, Q. Huang, and J. Huang, 2005. The Development, Challenges and Management of Groundwater in Rural China, in M. Giordano, and T. Shah, eds., *Groundwater in Developing World Agriculture: Past, Present and Options for a Sustainable Future*. Colombo, Sri Lanka: International Water Management Institute.

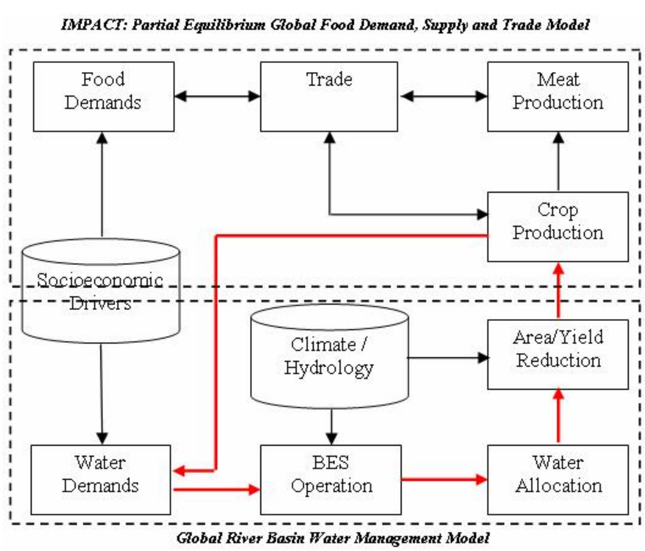
Zhang, W. 2003. The functions of rational development of groundwater resources in South to North Water Transfer Project, *South to North water Transfers and Water Science & Technology*, 1(4): 1-12, (In Chinese).

Figure 1: Share of households with access to electric and diesel pumps, respectively, Indian States



Source: National Sample Survey Data, India 1998

Figure 2: Conceptual framework of IMPACT-WATER model.



Note: Red arrow lines illustrate the linkages between the water and food models.

Figure 3 Global food production units (FPUs) in IMPACT-WATER

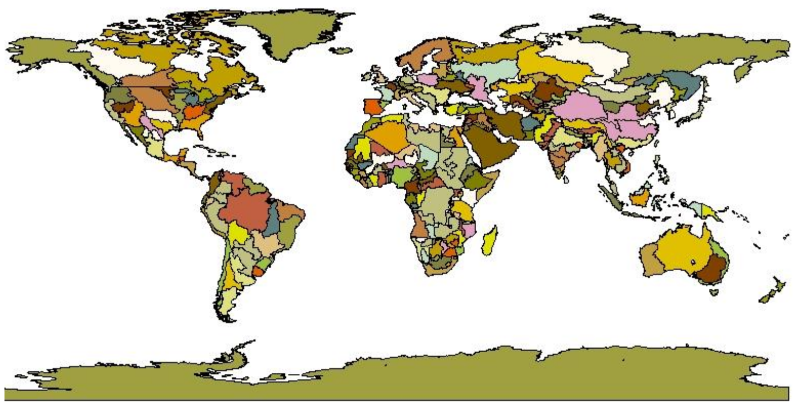


Figure 4 Price elasticity of irrigation water demand for selected countries

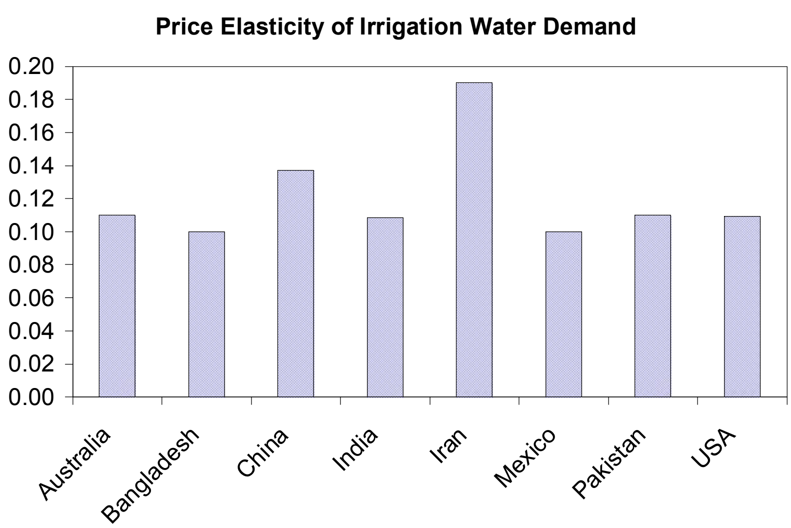


Figure 5: Projected irrigation water consumption, alternative groundwater pumping cost scenarios

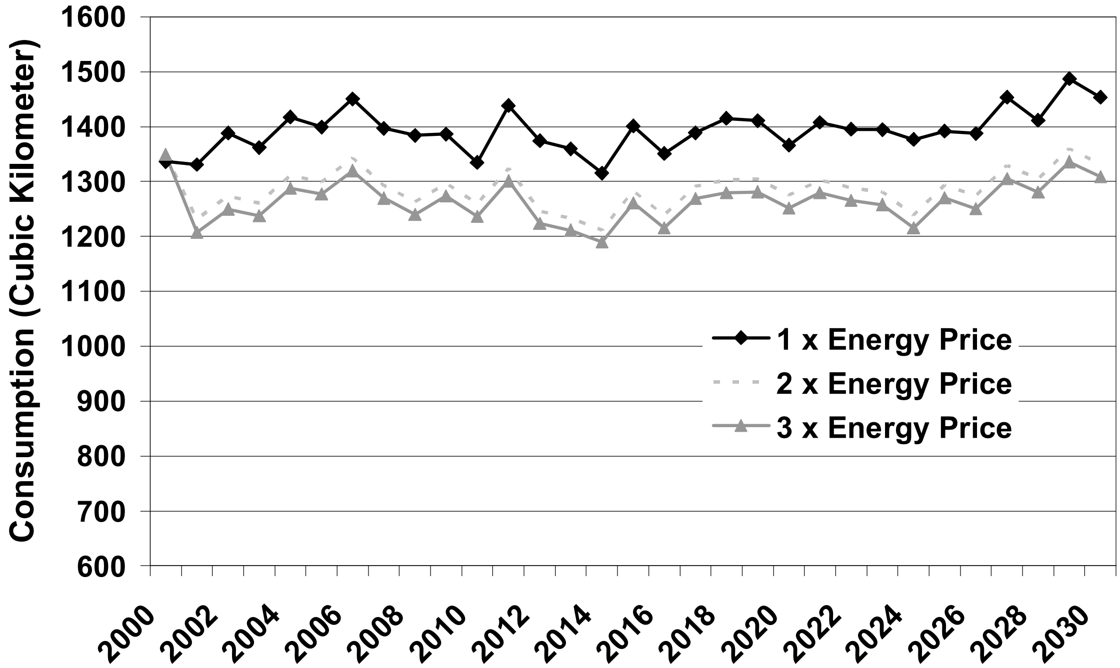


Figure 6: Projected international price for rice, alternative groundwater pumping cost scenarios

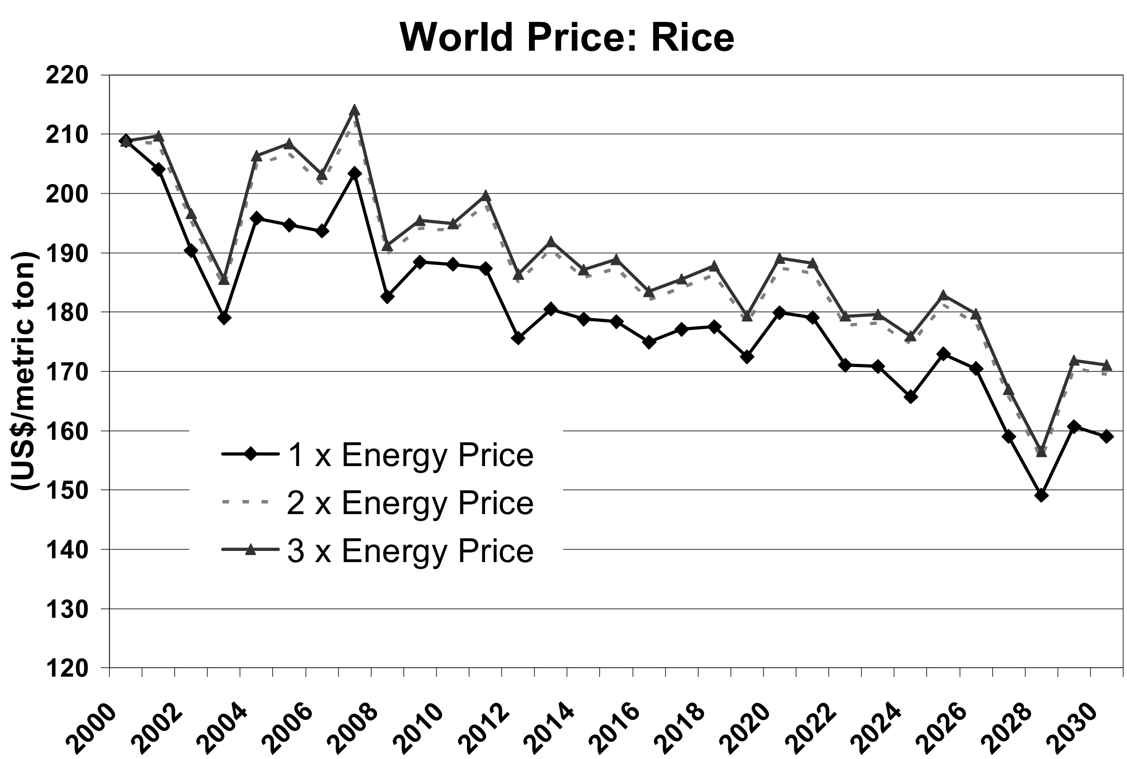


Figure 7: **Projected international price for maize, alternative groundwater pumping cost scenarios**

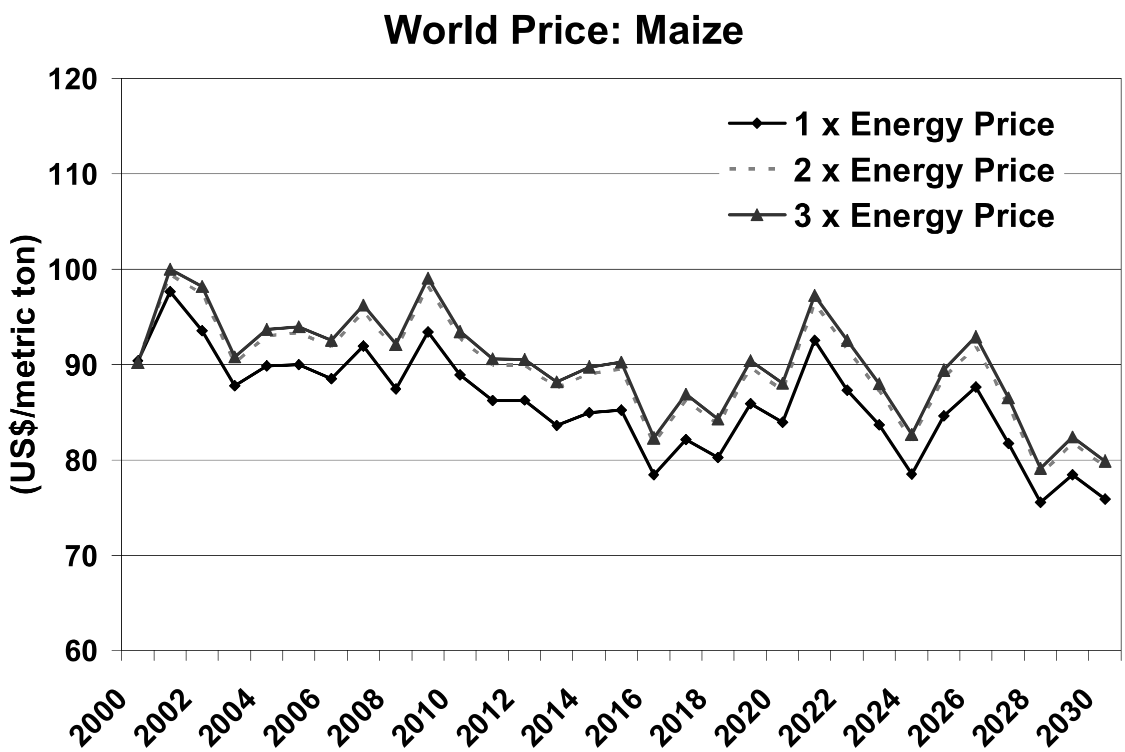


Figure 8: **Total groundwater withdrawals under alternative pumping cost scenarios, Dong Nai River Basin**

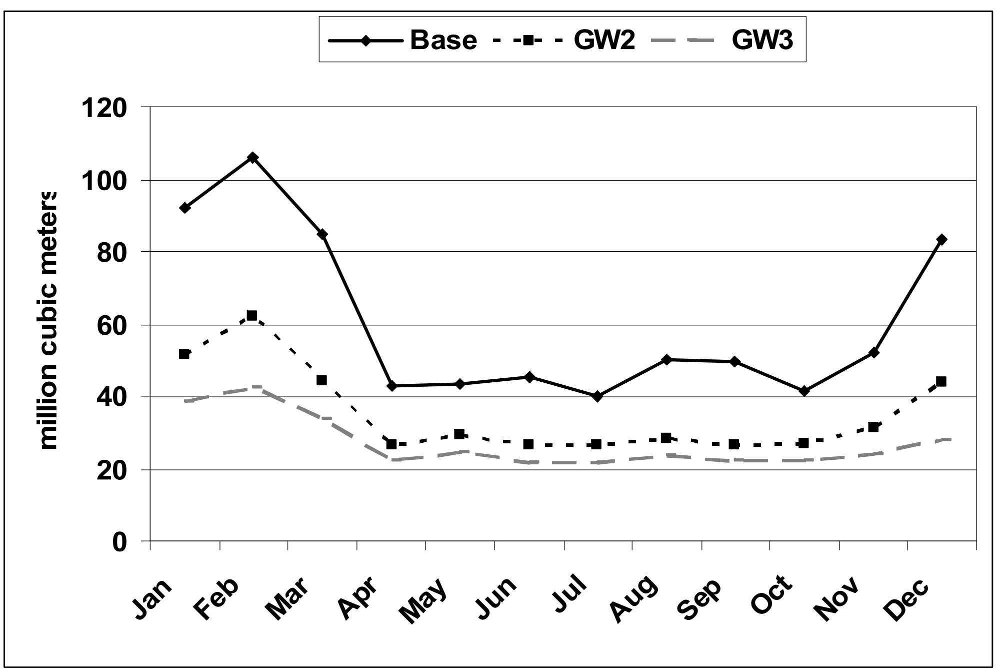


Figure 9: **Changes in area, yield, production for coffee, under alternative pumping cost scenarios, Dong Nai River Basin**

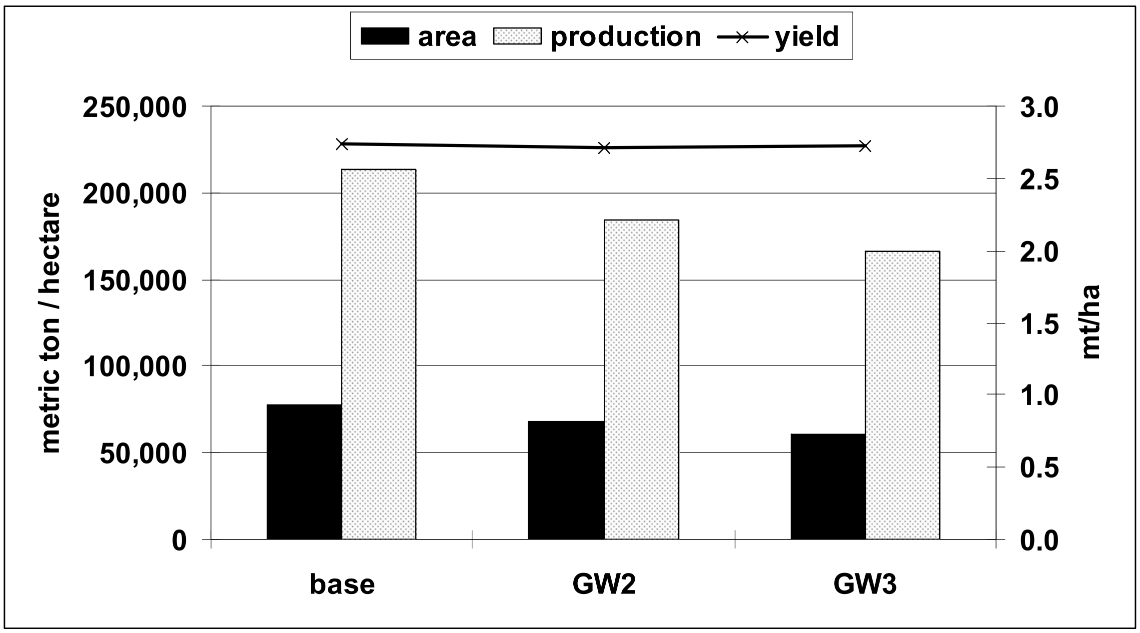
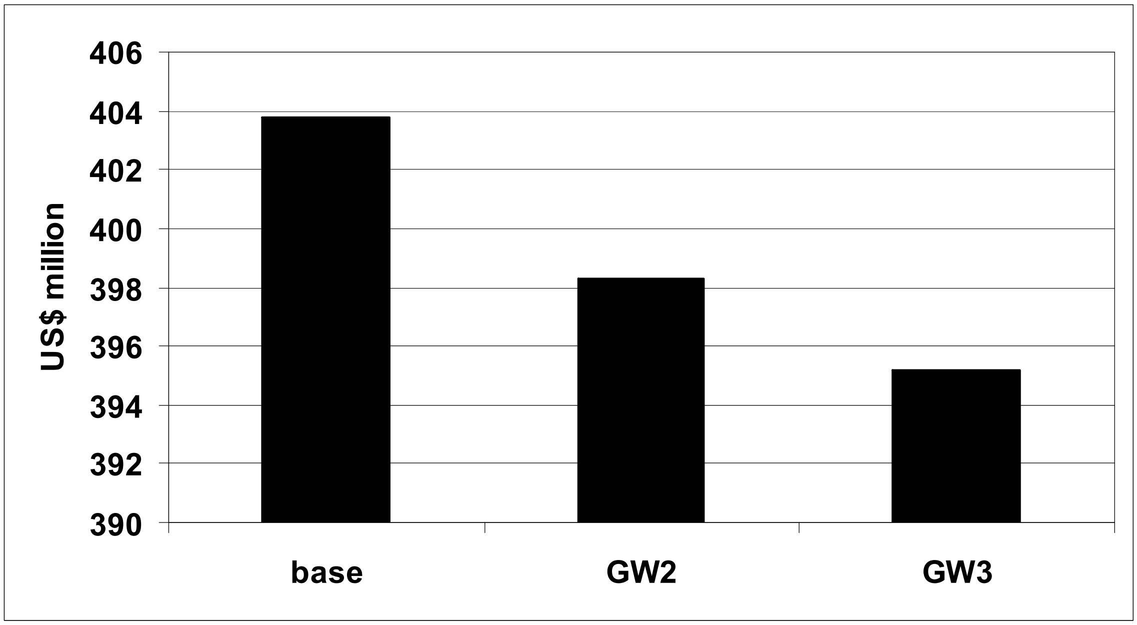


Figure 10: **Changes in profit from irrigated agricultural production, under alternative pumping cost scenarios, Dong Nai River Basin**


406
404
402
400
398
396
394
392
390
US$ million
base
GW2
GW3